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INVESTIGATION OF FLOW OVER PARTIALLY OPEN WIND TUNNEL WALLS

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FINAL REPORT

INVESTIGATION OF FLOW OVER PARTIALLY

OPEN WIND TUNNEL WALLS

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ABSTRACT

The mixing layer along a partly open wall is investigated experimentally in order to confirm a mixing theory based on a conical shear flow in which the mixing length is proportional to the width of the mixing layer.

TABLE OF CONTENTS

SYMBOLS

A	Cross-sectional area of test section
d	Width of test section
h	Height of test section
M	Momentum
m	Mass of air
m'	Dimensionless form
Δm	Suction mass
N_{Re}	Reynolds number
r'	Hydraulic radius
U	Velocity in x-direction
U_∞	Velocity of parallel flow
x, y	Rectangular co-ordinates
δ	Boundary layer thickness
ρ	Density of air
σ	Ratio of open area to total area
τ	Shear stress

v

FIGURES

I. INTRODUCTION

In recent years, transonic wind tunnels have been developed which use perforated walls in order to eliminate or reduce wall interference. It was observed that in these tunnels, the thickness of the friction layer of the wall increases more rapidly than in conventional slotted wall wind tunnels. This was thought to be due to mixing through the openings in the walls. In Ref. 1 a first attempt was made to explain quantatively the flow near the perforated wall. When these results were compared with experiments, it was found that they described the phenomena correctly, but that a more accurate theory would be desirable. In Ref. 2, a theory for the mixing layer along perforated walls was developed. This theory is based on the assumption of a conical shear flow, within which the mixing length, as defined by Prandtl, was assumed to be proportional to the width of the mixing layer. The constant of proportionality was assumed to be the same as that measured for open jet wind tunnels or wakes. This mixing zone was then subjected to a mean boundary condition at the wall which consists of the mean shear due to individual openings and solid portions between holes.

In the present report an attempt is made to check this theory, by careful experimentation at subsonic speeds.

This investigation is of some importance since, if the flow

near the wall is essentially of the mixing type, no appreciable gain in efficiency with increasing size can be expected in transonic wind tunnels.

II. EXPERIMENTAL INVESTIGATION

A. Apparatus

The Brown University subsonic wind tunnel was used to obtain the data for this report. The tunnel is of the open circuit type with the test section at atmospheric pressure. A 100 hp constant speed motor drives the compressor which generates speeds up to 200 fps in a 22 in. by 32 in. test section.

An opening 20 in. by 22 in. in one wall of the test section accommodated the various wall configurations. For the single slot and for the multi-slots the walls were made of aluminum and were arranged as follows:

(1) One transverse slot in the middle of the wall, four inches wide and with two different wall thicknesses one-quarter inch and one inch. For both wall thicknesses the edges were rectangular and beveled 45°, sharp edge to the free stream. The upstream edge of the slot was located 27 1/2 in. from the beginning of the test section.

(2) A slotted wall with eight one in. transverse slots at one and one-half inch intervals, $\sigma = .40$. The wall

thickness was three-eights inch and the edges rec-
tangular. The upstream edge of the first slot was
19 1/2 in. from the beginning of the test section.

The perforated wall was made of 0.050 in. brass sheet
with 0.3125 in. diameter holes arranged in a staggered hexagonal
pattern, with $\sigma = .40$. The solid test section wall downstream of
the wall opening provided a total test area 22 in. by 32 in. The test
wall was open to the atmospheric pressure of the room.

All pressure measurements were made with a Betz-type
water manometer with direct reading to 0.1 mm of water. The
boundary layer profiles were obtained using a single total pressure
probe flattened to read a minimum of 0.015 in. from the wall. A
micrometer head was used to measure distances from the wall into
the air stream.

B. Procedure

The tunnel was run at a constant air speed of 116 fps,
which corresponds to a Reynolds number of 61,500/in. Pressure
measurements were made to obtain the boundary layer profiles for the
solid wall at stations one in. apart over the last 32 in. of the 50 in.
length of test section.

Boundary layer profiles were obtained for the six different
wall openings at stations one inch apart, beginning at the upstream edge
of the open area and continuing over the solid portion downstream. The

upstream edge of the four inch slot was taken as zero inch reference.

III. TEST RESULTS

A. Suction Requirement

In Figs. 1 through 10 the boundary layer profiles for the six different wall openings together with the solid wall profiles are shown for two inch intervals over the test area in the direction of flow, starting at the upstream edge of the open area.

Let Fig. 11 represent the test section of the wind tunnel. If the divergence of the walls is adjusted such that the pressure is constant in the test section, the following calculations can be made regarding the mass leaving through the wall openings:

The mass passing through the test section at station x is

$$m(x) = d \int_0^h \rho \, U \, dy$$

If a solid wall is employed, this mass is constant and equal to m_0, where

$$m_0 = d \int_0^h \rho \, U_{solid} \, dy$$

Thus we obtain the mass that left the partially open test section up to station x as

$$\Delta m(x) = m_0 - m(x)$$

$$= \rho \, U_\infty \, d \int_0^d \left(\frac{U_{solid}}{U_\infty} - \frac{U}{U_\infty} \right) dy$$

5

where the integration limit h is replaced by the shear layer thickness δ, since outside this layer the integrand vanishes.

Reducing this to dimensionless form analogous to Ref. 1

$$m' = \frac{r'}{x} \frac{\Delta m}{\rho U_\infty A}$$

where $r' = \frac{A}{d} = h =$ hydraulic radius of partly open wall

$$m'x = \int_0^\delta \left\{ \frac{U_{solid}}{U_o} - \frac{U}{U_o} \right\} dy$$

The quantity m' is equivalent to the ratio of the mass passing through an open wall area equal to the tunnel cross-sectional area to the mass entering the tunnel.

The results of m'x versus x obtained by graphical integration, using a planimeter, are shown in Figs. 12 through 14. The solid curve represents the theoretical result, which for the four inch slot, Fig. 12, can be calculated from the theory of Ref. 1, where m' = 0.01023 for the open jet. For the slotted wall, Fig. 13, and for the perforated wall, Fig. 14, the calculated result for m' was determined by the theory of Ref. 2.

$$\text{slotted wall} \qquad m' = 4.45 \times 10^{-3}$$
$$\text{perforated wall} \qquad m' = 5.62 \times 10^{-3}$$

B. Shear Stress

The momentum flux at a station x of Fig. 11 is given by

$$M(x) = \rho d \int_0^h U^2 dy$$

This flux must equal the flux at station O minus the shear force acting

up to this station minus the momentum lost due to the outflow, since

no pressure gradient is present.

$$M(x) = M(0) - d \int_0^x \tau dx + \int_0^x \frac{dm}{d\xi} U(\xi)_{y=0} d\xi$$

thus the shear stress is obtained as

$$\tau = -\rho \frac{d}{dx} \int_0^h U^2 dy + U(x)_{y=0} \frac{dm}{dx}$$

$$\tau = -\rho \frac{d}{dx} \int_0^h U^2 dy - U(x)_{y=0} \rho U_\infty m'$$

or in dimensionless form

$$\frac{\tau}{\rho U_\infty^2} = -\frac{d}{dx} \int_0^h \left(\frac{U}{U_\infty}\right)^2 dy - \frac{U(x)_{y=0}}{U_\infty} m'$$

Using this equation, the shear stress was determined

graphically from the boundary layer profiles and plots of U^2/U_∞^2

for the solid, slotted, and perforated walls. The results are shown

in Figs. 15, 16, and 17. The dotted curve in each case is the shear

stress of the solid wall.

For the four inch slot, Fig. 15, the solid curve represents

the theoretical value of the shear stress found using open jet theory,

and is read directly from Fig. 2 Ref. 2.

The theoretical values of mean shear stress for the slotted

wall Fig. 16, and for the perforated wall, Fig. 17, were calculated

according to the method outlined in Ref. 2. The values obtained in each case were as follows:

Slotted Wall	Perforated Wall
$\sigma = .40$	$\sigma = .40$
$N_{Re} = 4.35 \times 10^{4}$	$N_{Re} = 4.75 \times 10^{4}$
$C_{D_t} = 0.01193$	$C_{D_t} = 0.01923$
$\dfrac{\tau}{\rho U_{\infty}^{2}} = 6.80 \times 10^{-3}$	$\dfrac{\tau}{\rho U_{\infty}^{2}} = 7.67 \times 10^{-3}$

The Reynolds number is referred to the wetted length between openings in the wall, and C_{D_t} is the surface drag coefficient. C_{D_t} is a function of the Reynolds number.

IV. CONCLUSIONS

The experimental results for flow through partly open walls are in agreement with the assumption that this type of flow is a mixing process. This is indicated by the fact that the experimental results for the suction requirement compare favorably with the theoretical values, since the mixing length is a function of the suction requirement and the wall divergence.

The boundary layer profiles on the solid wall downstream of the open area show that the mixing layer is carried along and moves into the air stream as the new sublayer is formed.

In the case of the four inch slot, where the wall thickness and edge shape were varied, there was little effect on the results for

the different configurations, and downstream of the slot the boundary layer profiles are similar. Since the slot shows mixing of the open jet type, the Reynolds number has no influence.

The results for the slotted wall and the perforated wall indicate that a mixing theory based on conical shear flow has some validity, since one can predict the influence of the Reynolds number based on flow over solid portions of the flow pattern by determining the shear stress. The theoretical value for the shear stress was lower in each case.

REFERENCES

1. P. F. Maeder and   Investigation of Flow through a
   J. F. Stapelton   Perforated Wall.   Division of
                              Engineering, Brown University
                              Technical Report WT-10, May,
                              1953.

2. P. F. Maeder   Turbulent Mixing Along Perforated
                             Walls. ARO, Inc., July, 1954.

FIG. 1 BOUNDARY LAYER PROFILES — 4" SLOT

Legend:

- – – – – SOLID WALL PROFILES
- ——— 1/4" WALL THICK., RECT.
- – · – · 1" " " , "
- – – – 1/4" " " , 45° EDGE
- – ·· – 1" " " , " "

Axis labels: $\frac{U}{U_\bullet}$ (vertical), Y(in.) (horizontal)

Curves labeled: 2", 4", 6"

10
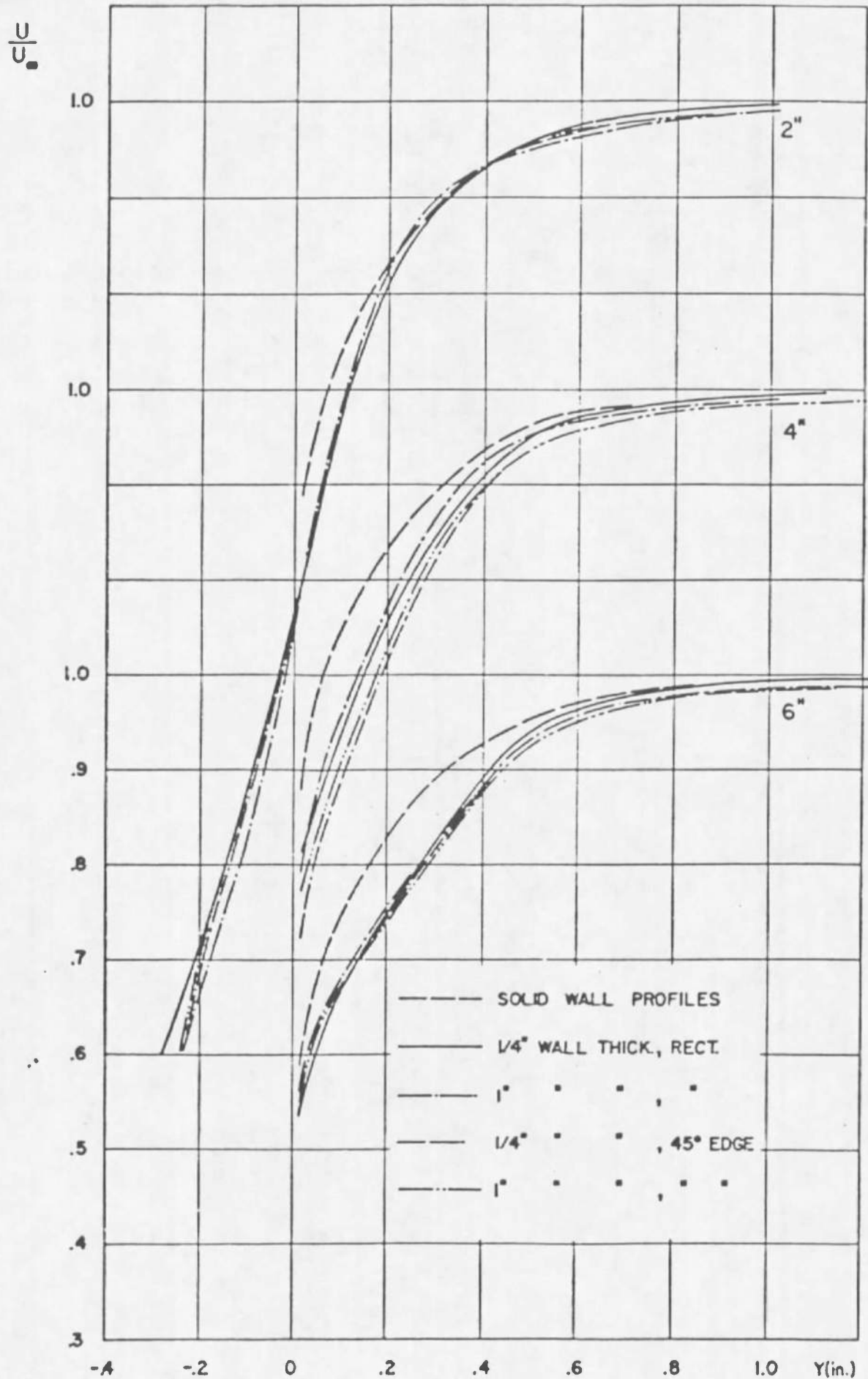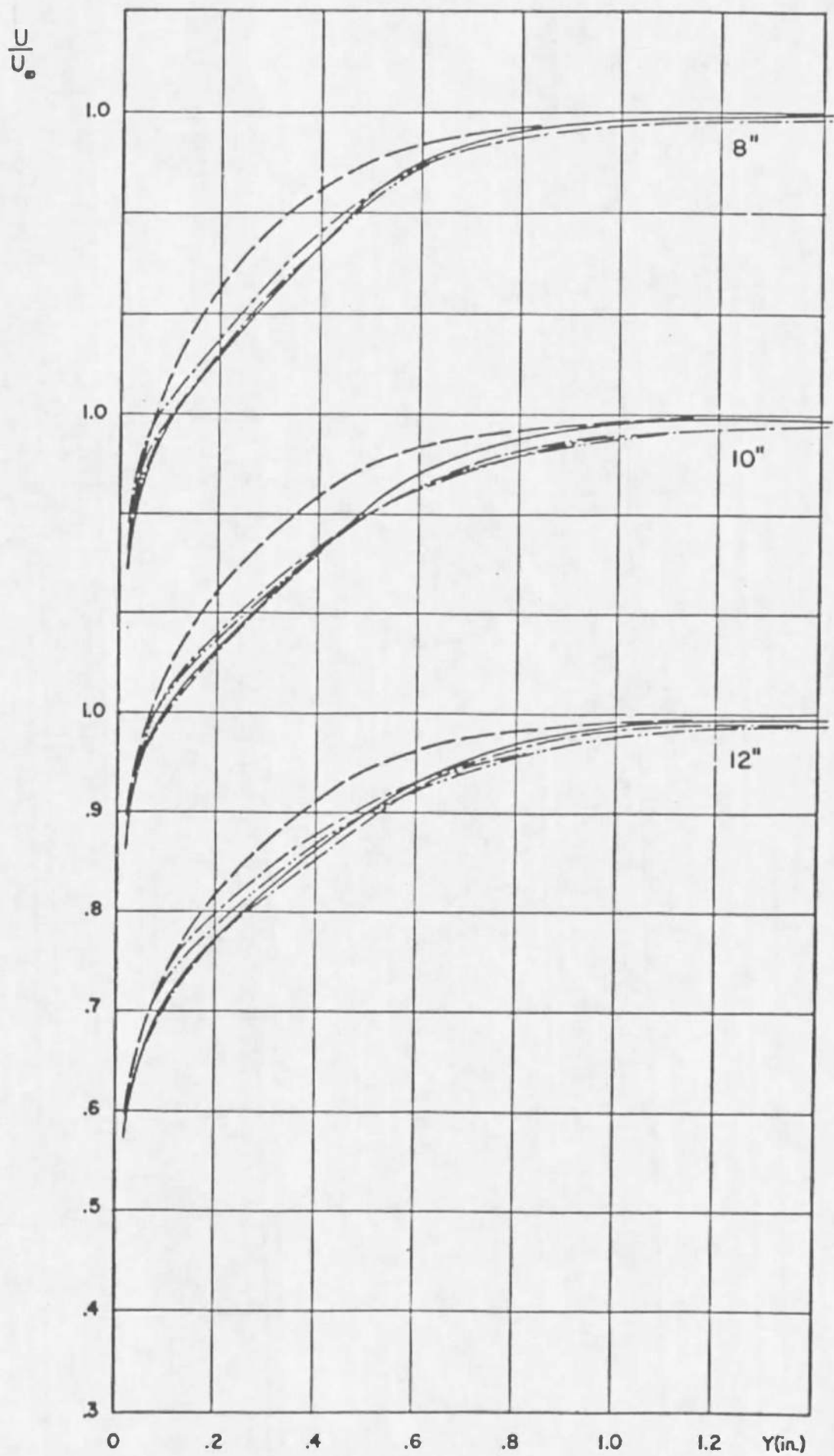
FIG. 2 BOUNDARY LAYER PROFILES — 4" SLOT
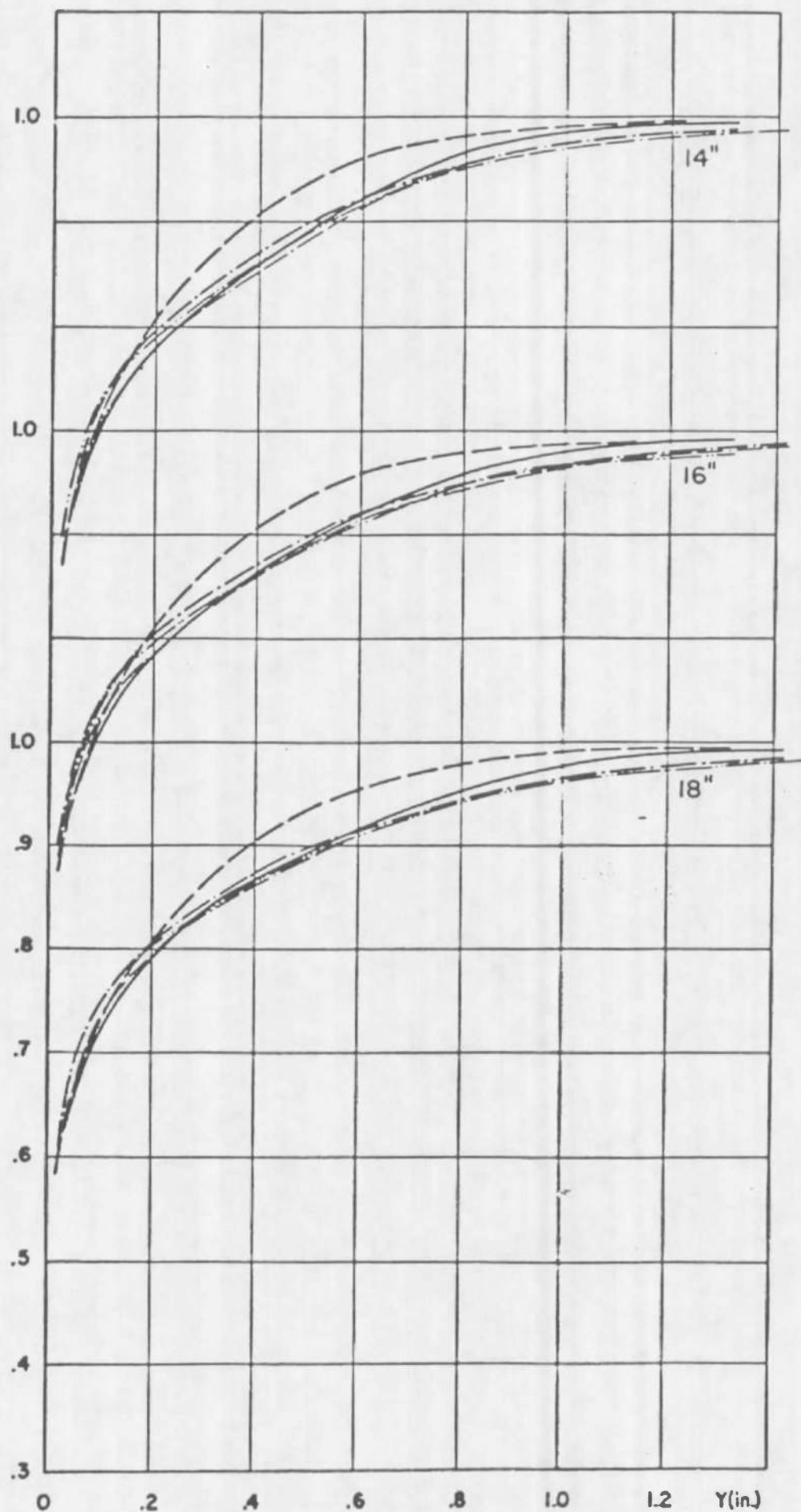
FIG. 3 BOUNDARY LAYER PROFILES – 4" SLOT
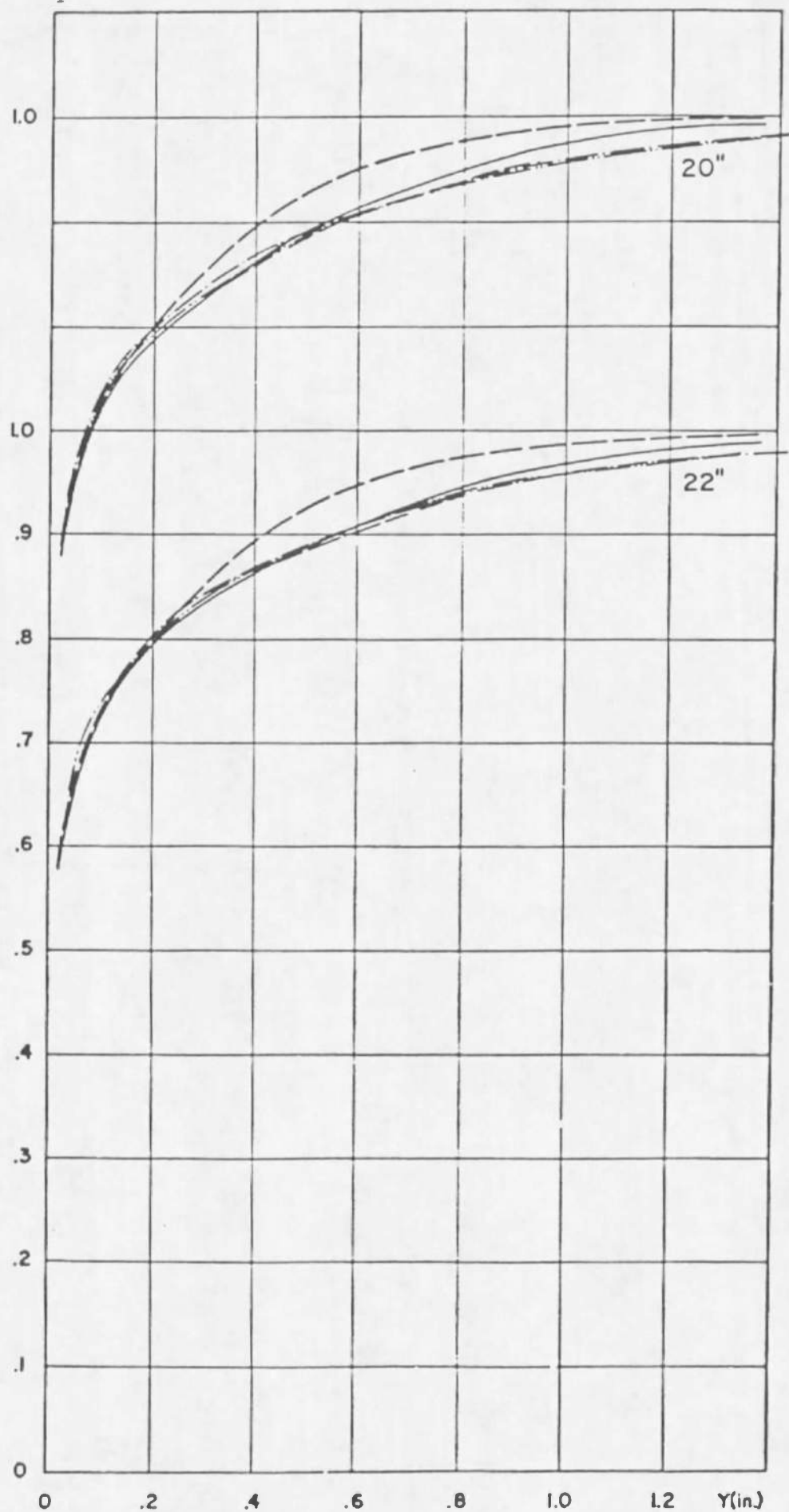
FIG. 4 BOUNDARY LAYER PROFILES — 4" SLOT

13
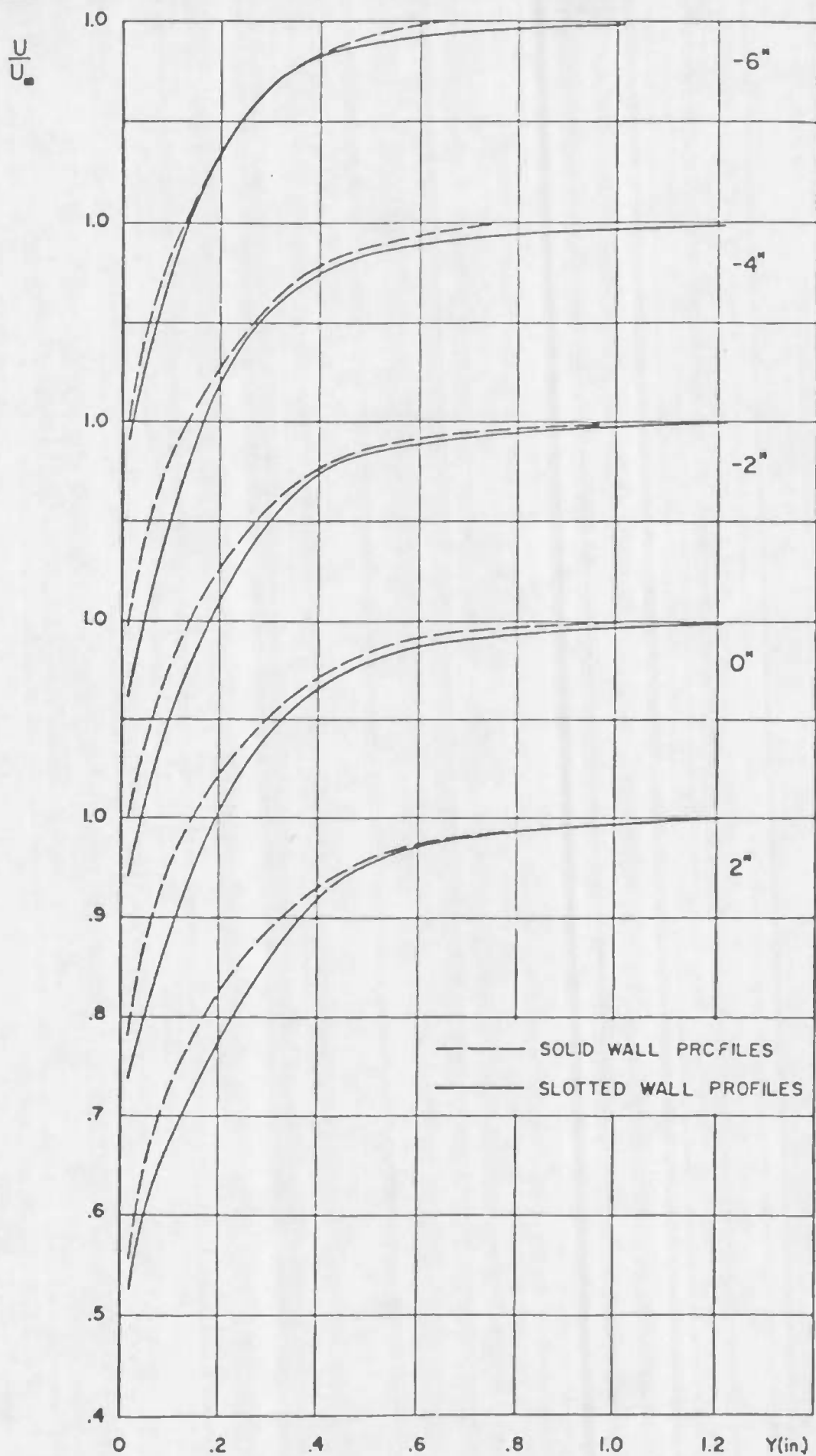
FIG. 5 BOUNDARY LAYER PROFILES — SLOTTED WALL

14
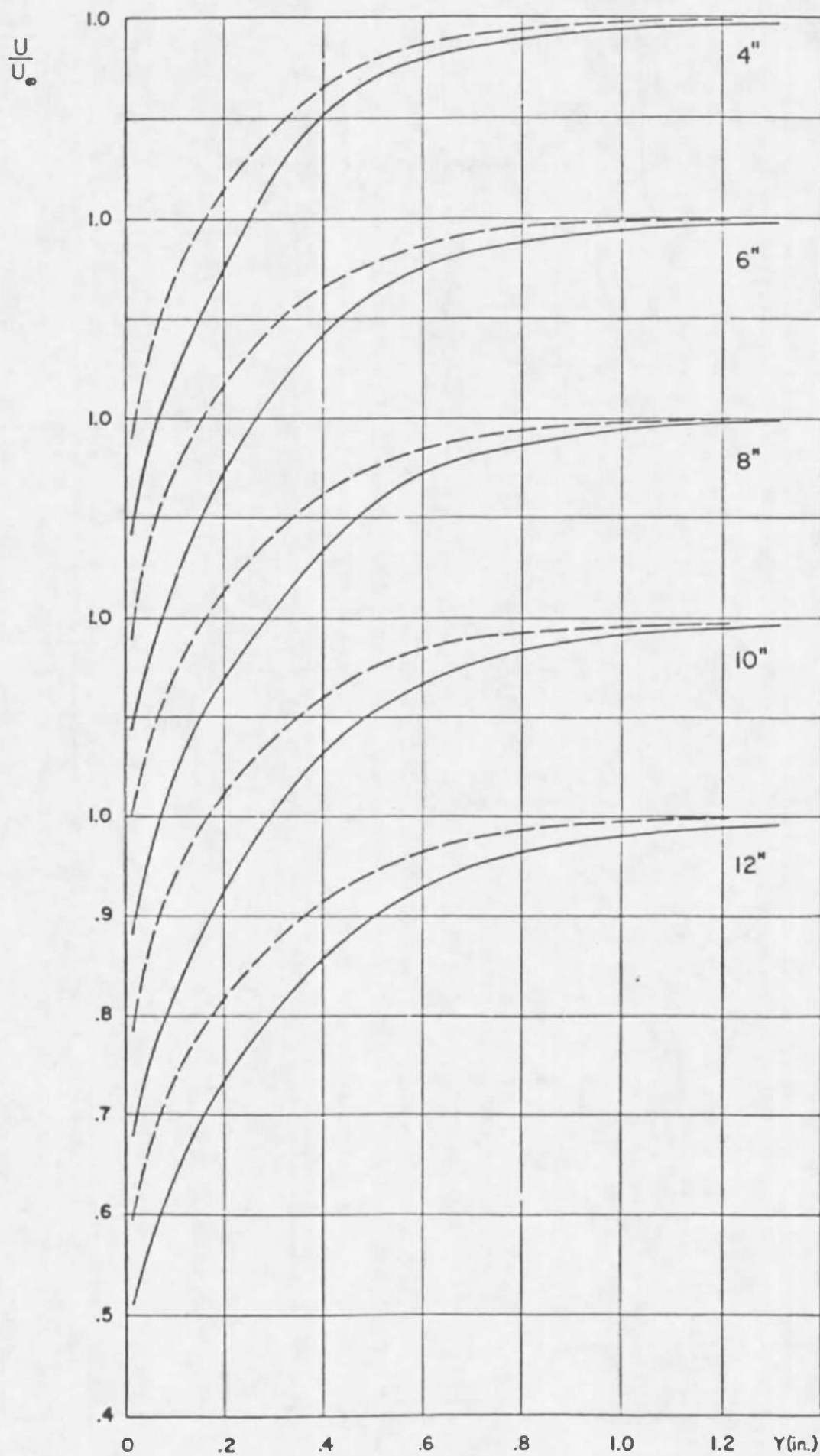
FIG. 6 BOUNDARY LAYER PROFILES - SLOTTED WALL

15
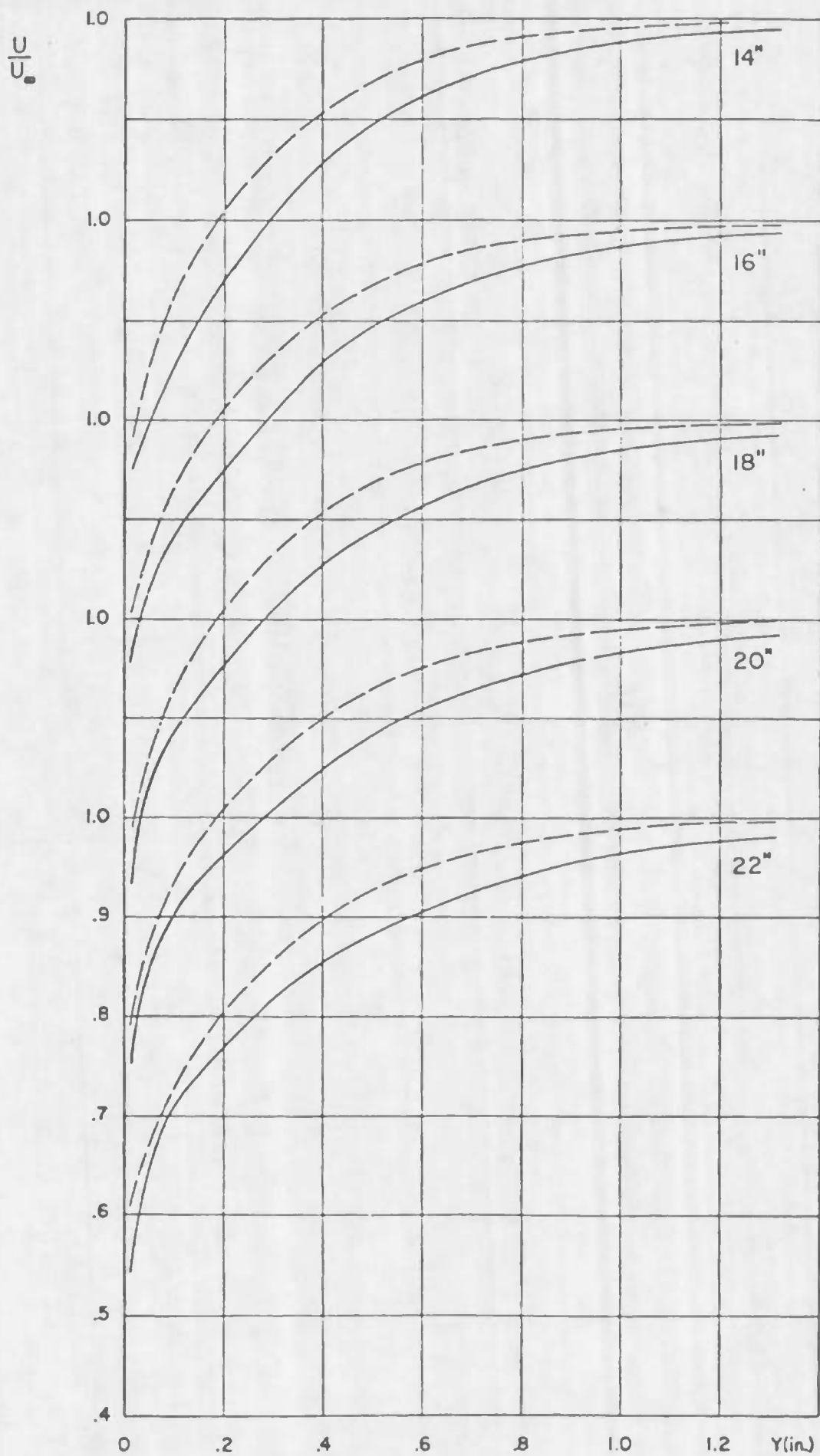
FIG. 7 BOUNDARY LAYER PROFILES – SLOTTED WALL

16
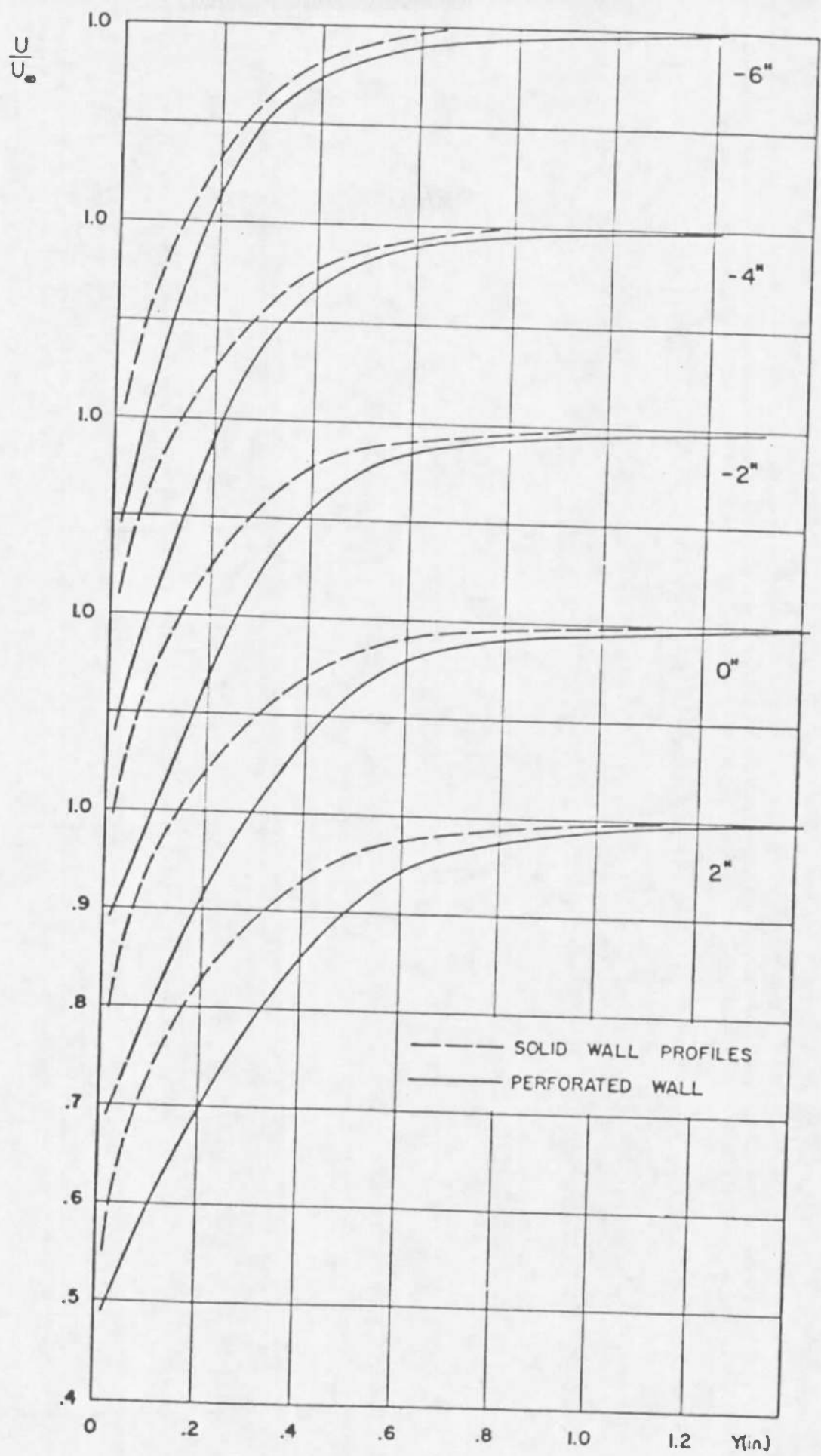
FIG. 8 BOUNDARY LAYER PROFILES — PERFORATED WALL
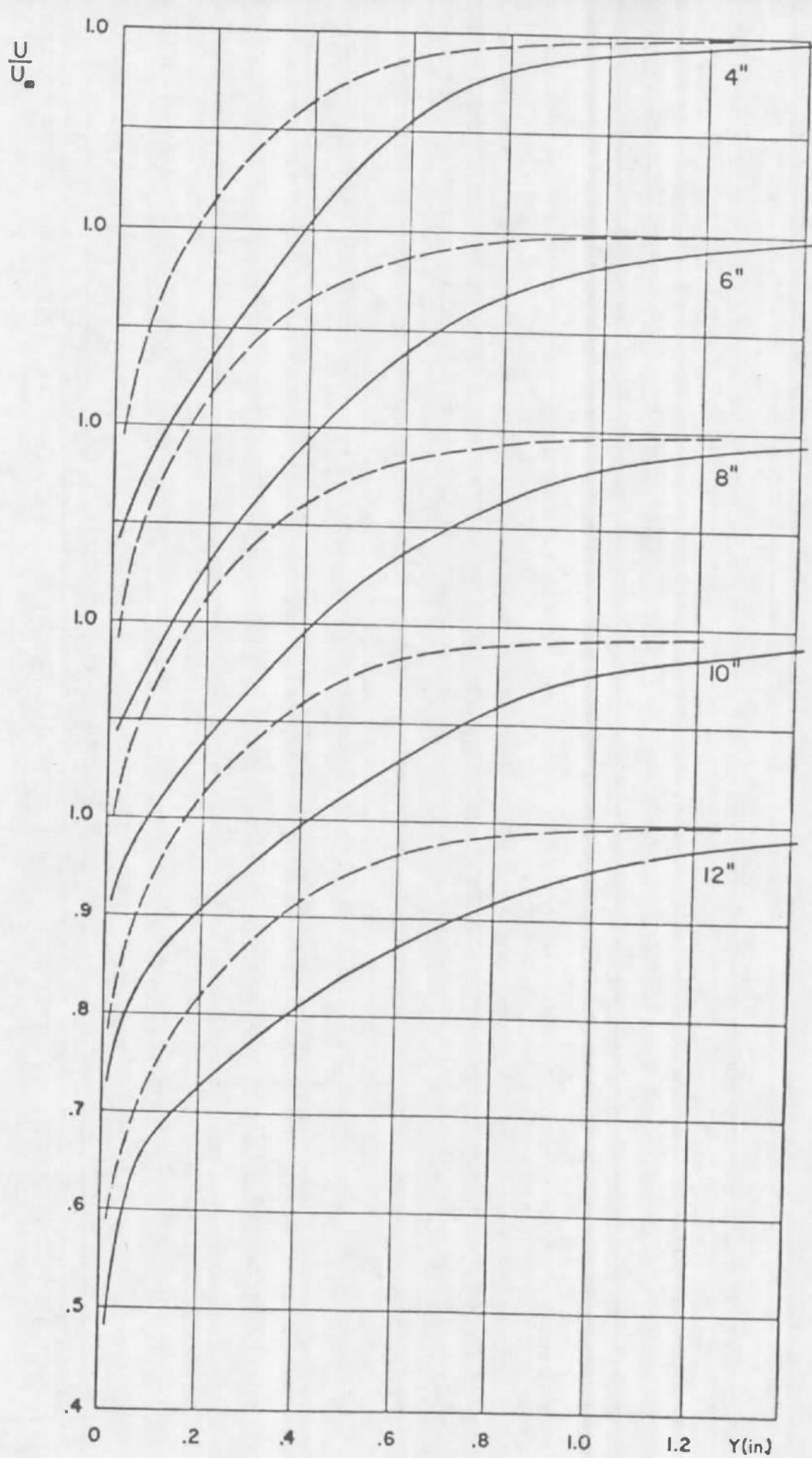
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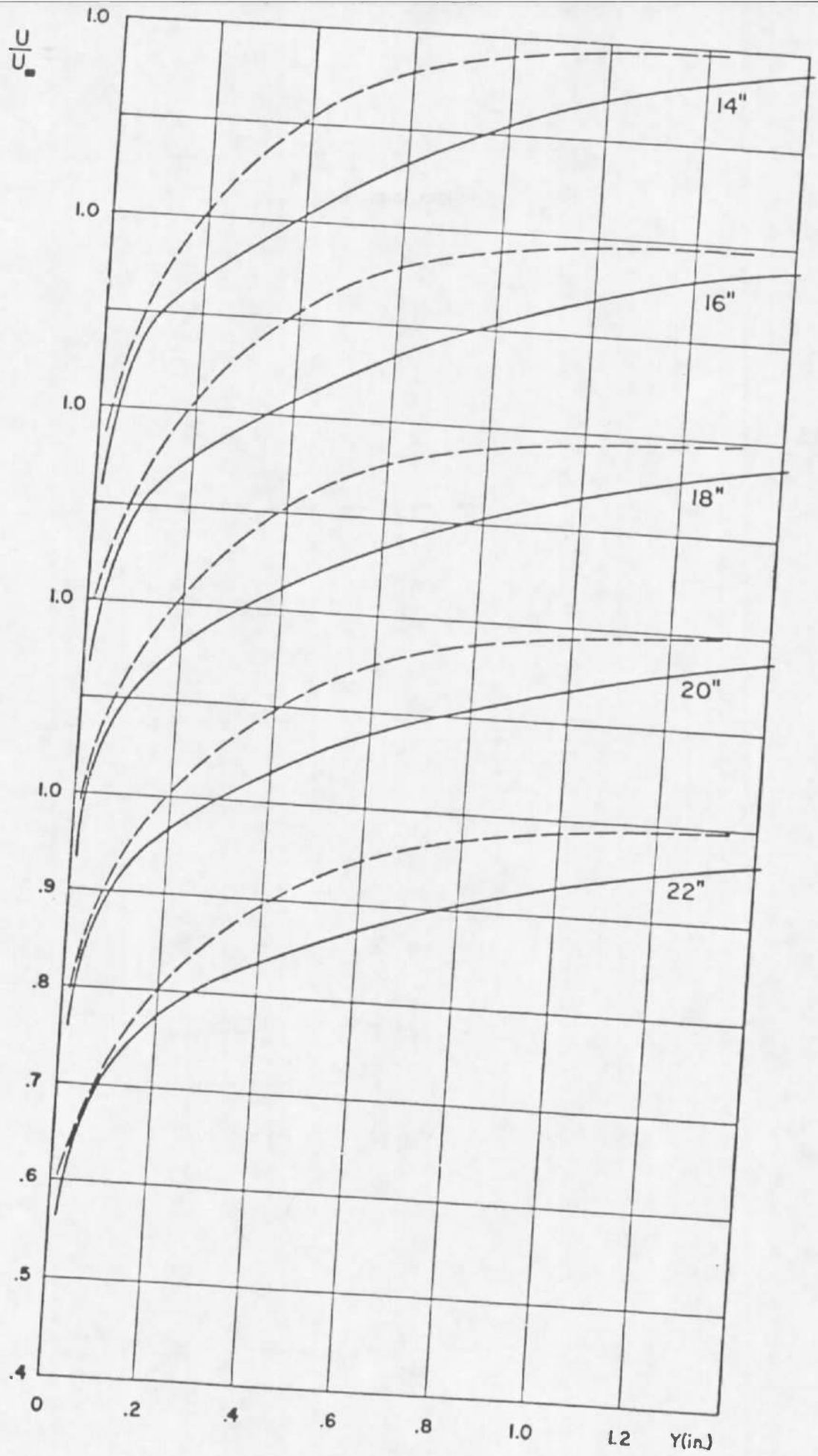FIG. 9 BOUNDARY LAYER PROFILES — PERFORATED WALL
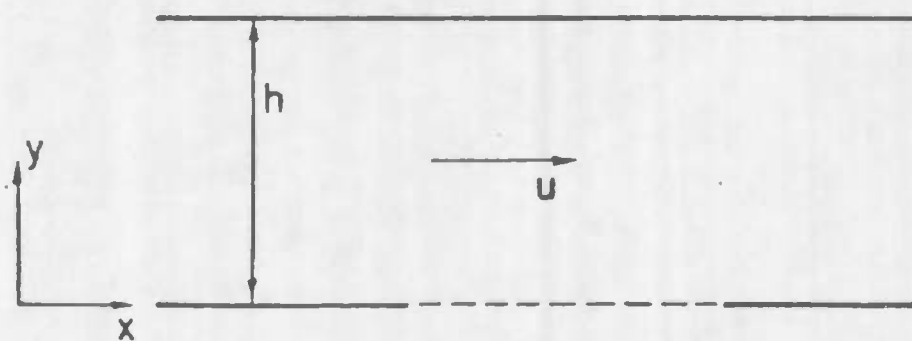
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FIG. 10 BOUNDARY LAYER PROFILES — PERFORATED WALL

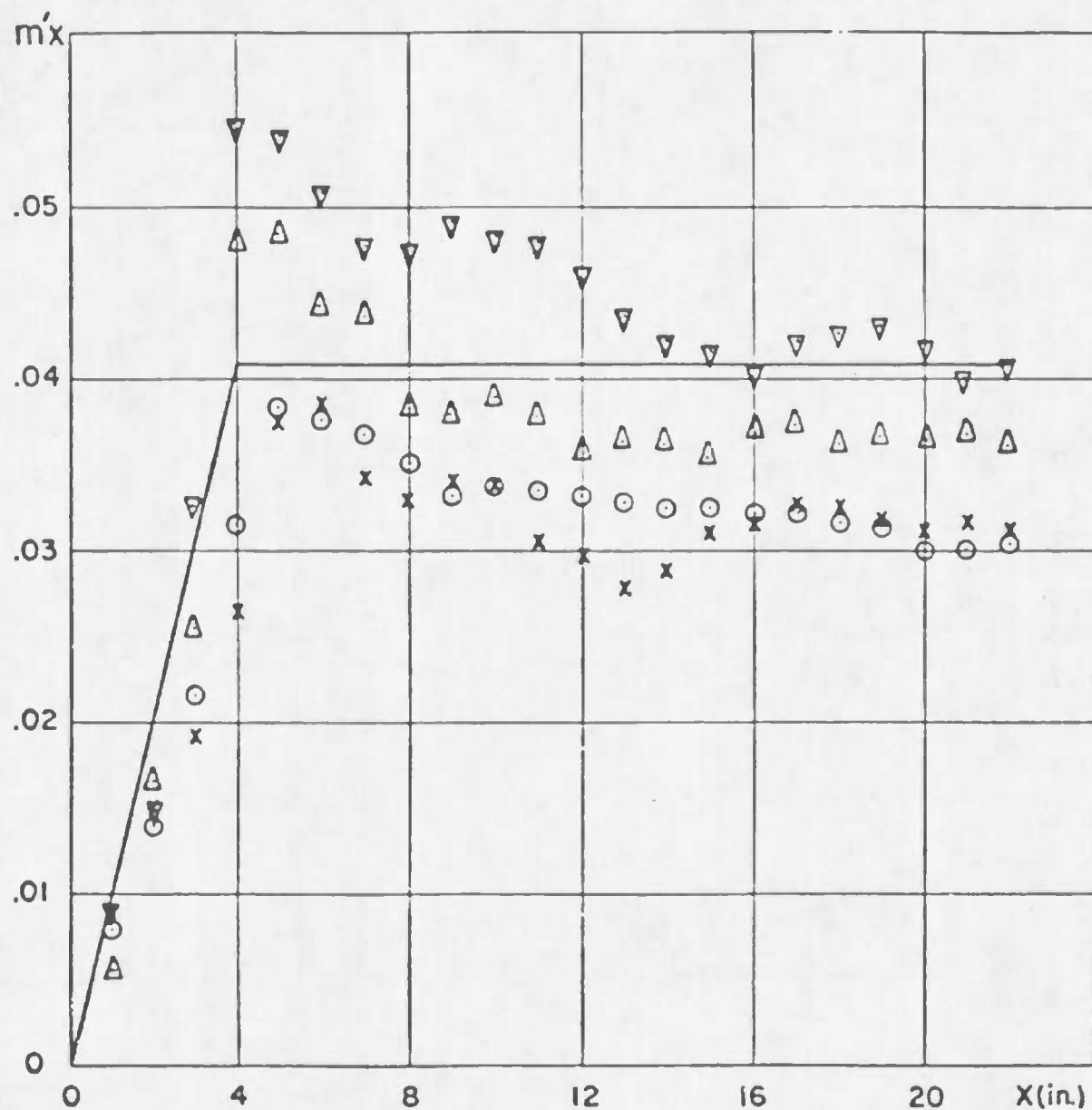FIG. II REPRESENTATION OF WIND
TUNNEL TEST SECTION
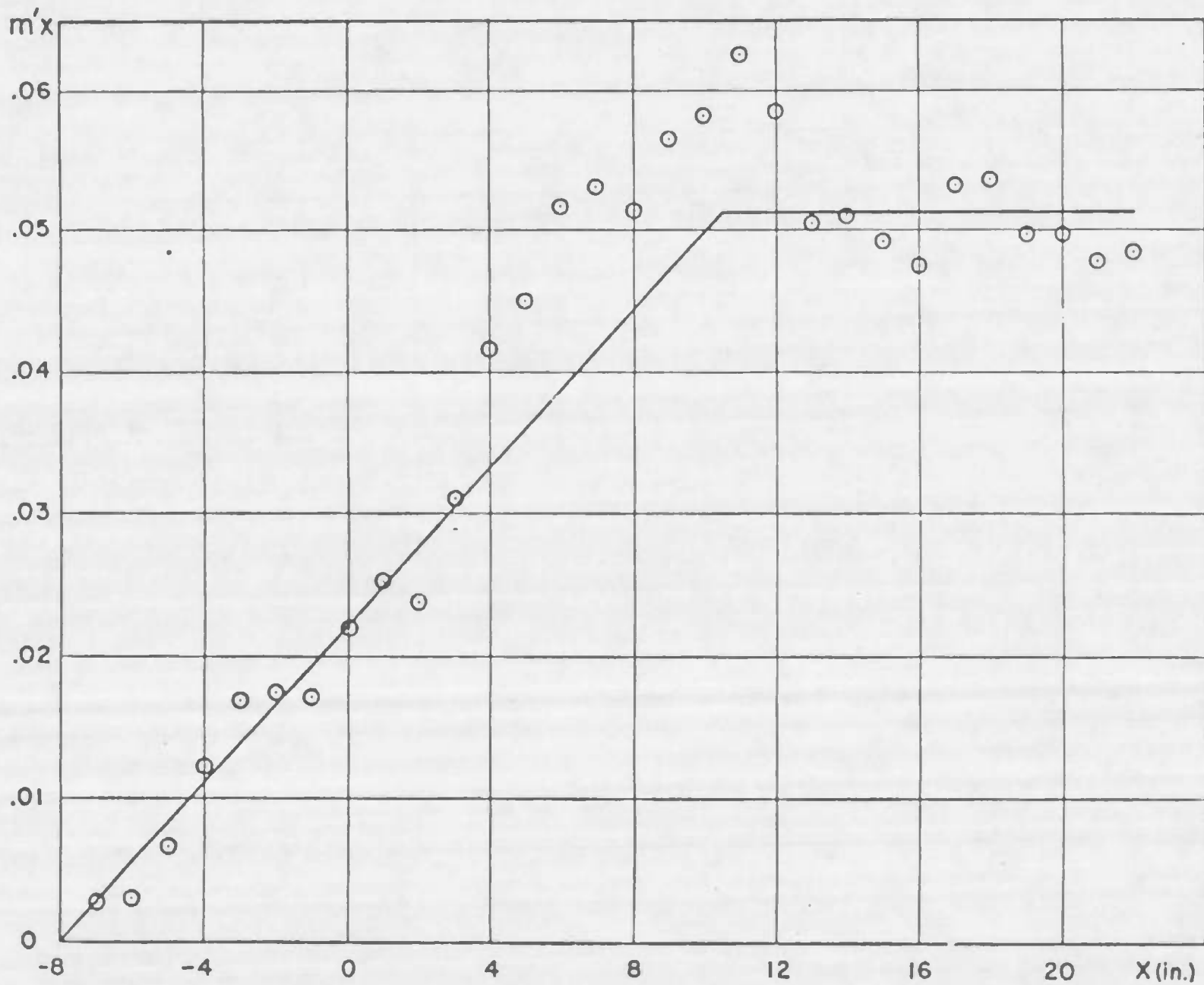
20

FIG. 12 SUCTION REQUIREMENT FOR THE 4" SLOT

Legend:
⊙ 1/4" WALL THICKNESS, RECTANGULAR EDGES
× 1"   "   "   "   ,   "   "
▽ 1/4" "   "   "   , 45° EDGES
▲ 1"   "   "   "   ,   "   "

FIG. 13   SUCTION   REQUIREMENT   FOR   THE   SLOTTED   WALL
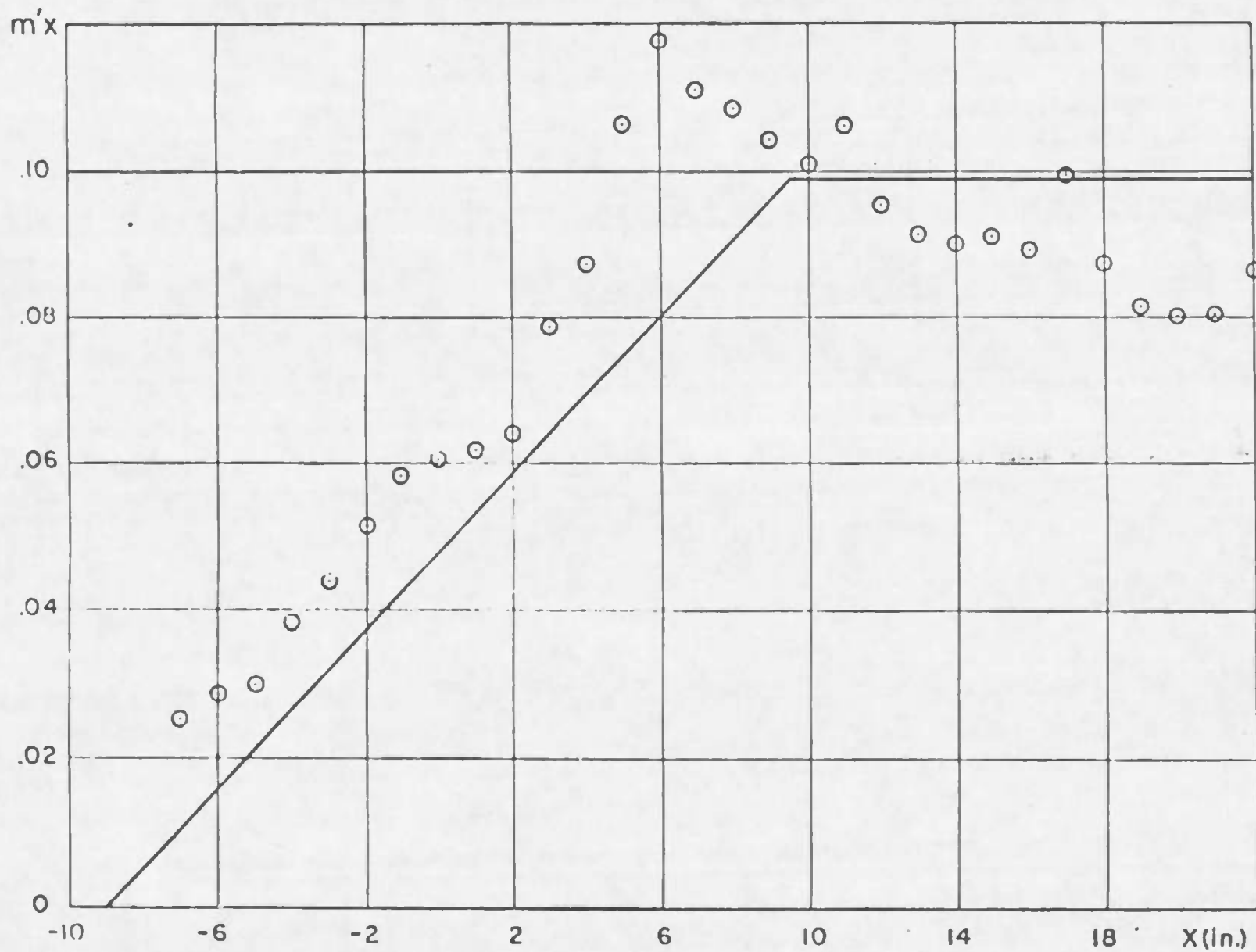
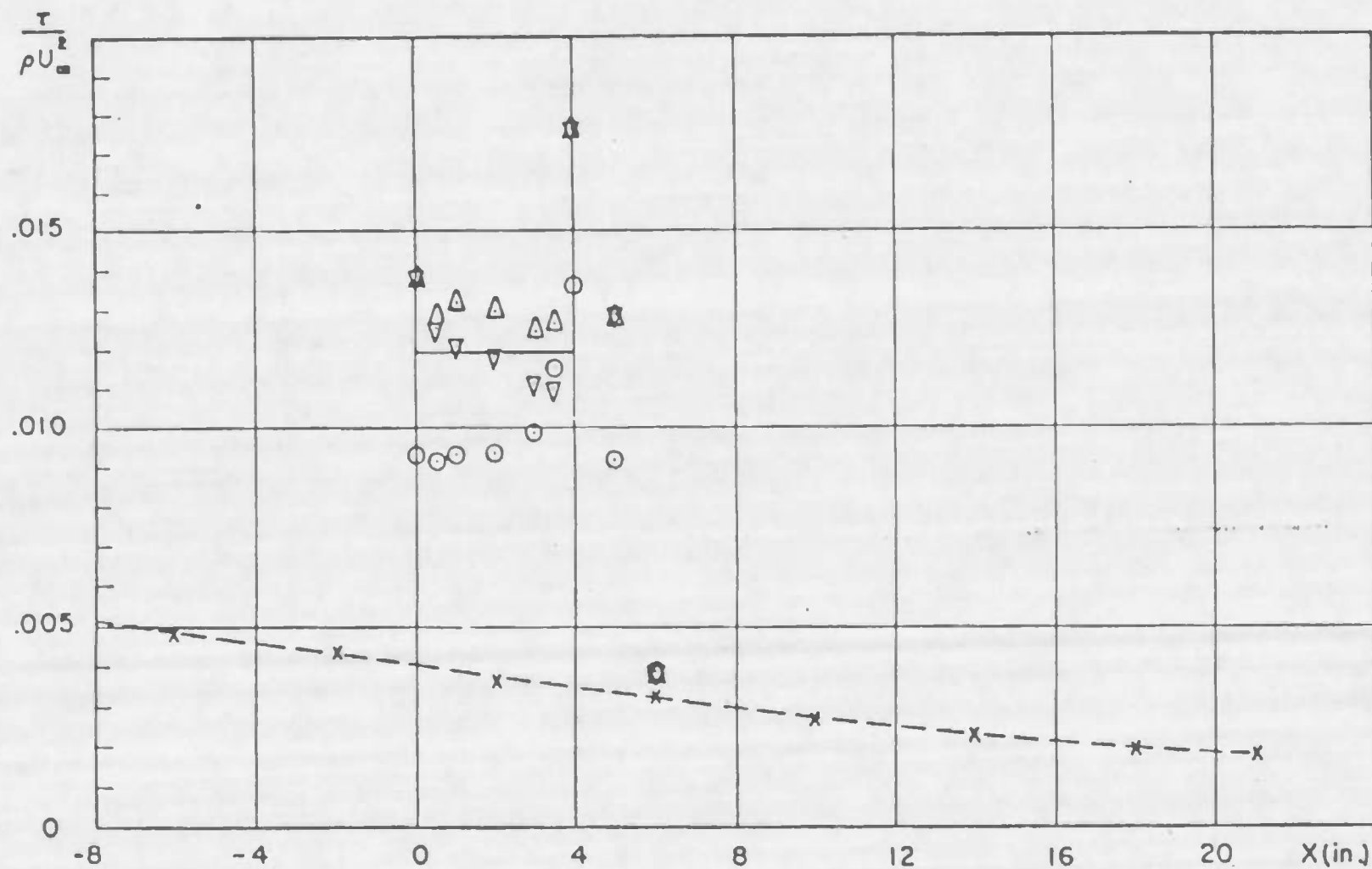FIG. 14   SUCTION   REQUIREMENT   FOR   THE   PERFORATED   WALL

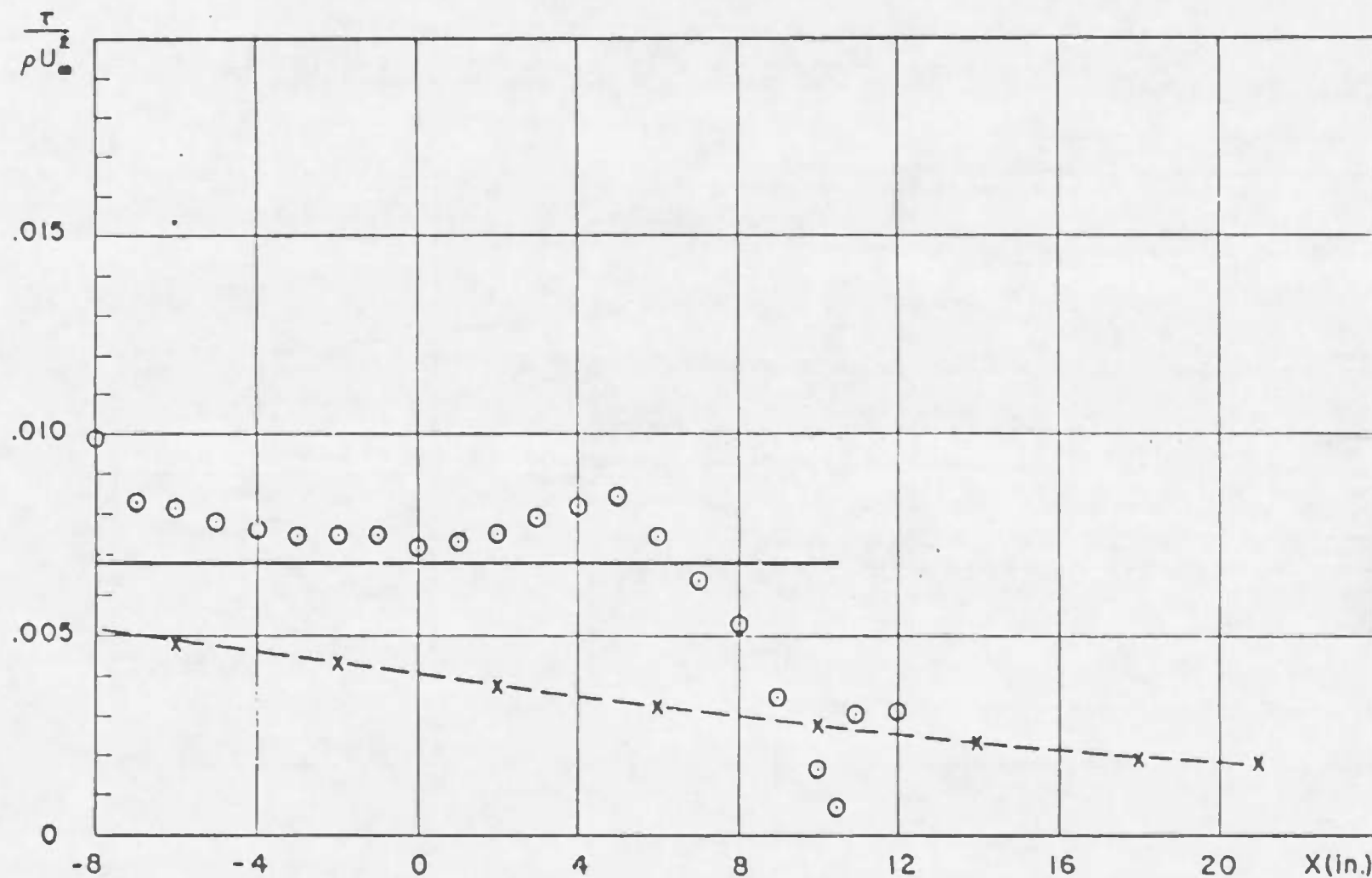FIG. 15   SHEAR STRESS FOR THE   FOUR   INCH   SLOT

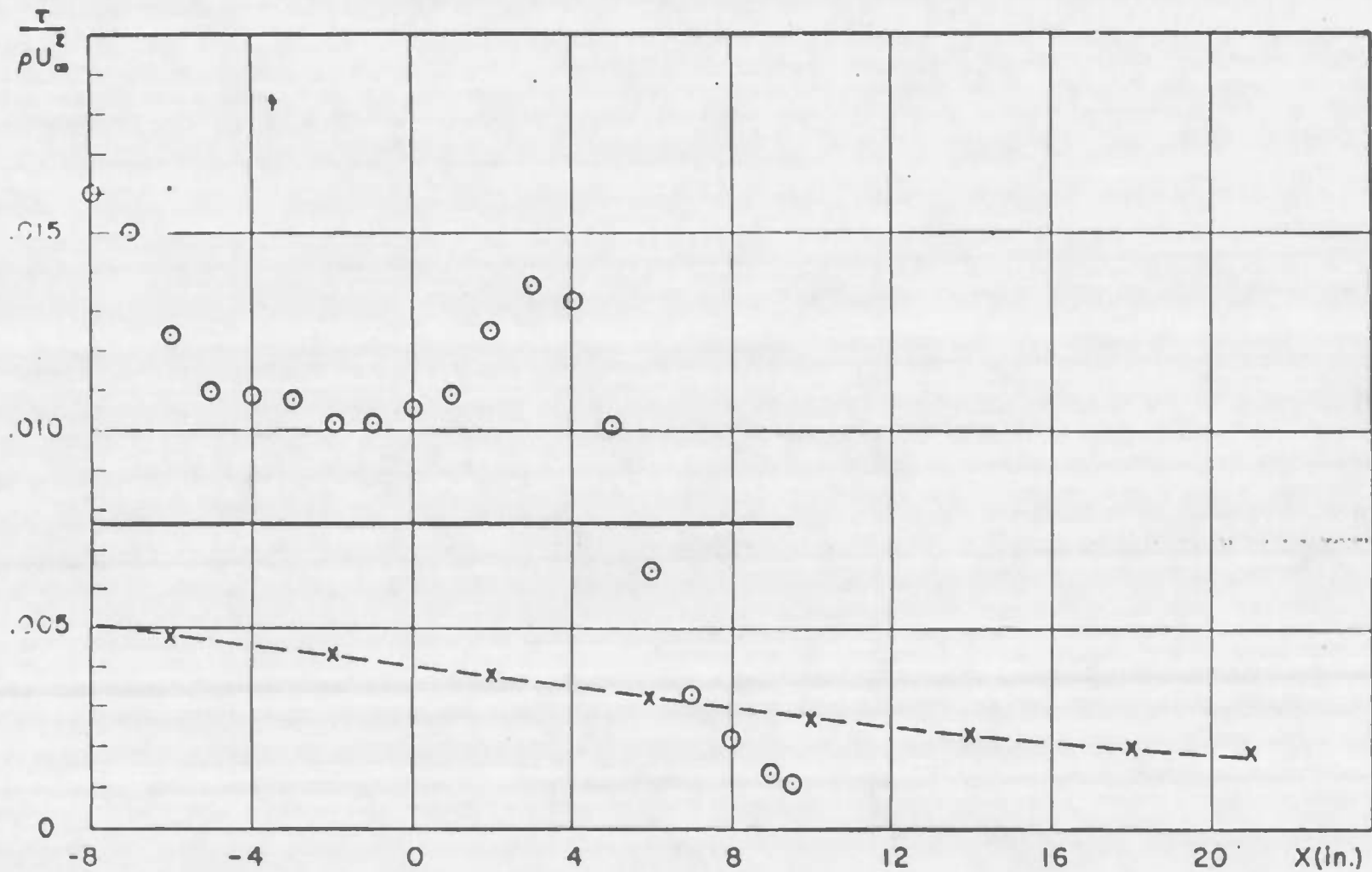FIG. 16   SHEAR STRESS ALONG THE SLOTTED WALL

FIG. 17   SHEAR STRESS ALONG THE PERFORATED WALL

BIBLIOGRAPHICAL CONTROL SHEET

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12. Abstract:

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